ARRIVAL TIME OF NITROGEN TO JOHNS POND IN A SEWAGE PLUME, CAPE COD, MASSACHUSETTS

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ABSTRACT

From 1936 to 1995, sewage was released through sand infiltration beds at Joint Base Cape Cod. The result was a contaminant plume within the groundwater that now extends over 8 km. Glacial processes that occurred during the end of the Pleistocene epoch deposited an unconsolidated, well-sorted coarse sand and gravel deposit that now acts as an unconfined aquifer and is the main source of drinking water in the region. One of the many concerns regarding this plume is the discharge of nitrogen containing species (i.e., nitrate and ammonium), and their potential effects on nearby Ashumet Pond and Johns Pond. Data from previous studies and the U.S. Geological Survey from 1999 were used to estimate qualitatively the time it would take for nitrate and ammonium in the groundwater to reach Johns Pond from an area immediately northwest of Ashumet Pond. It was found that nitrate has likely already infiltrated Johns Pond since 2016 at the latest, and that the flux of ammonium has just started arriving in Johns Pond and could persist for up to two decades.

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INTRODUCTION

For over half a century, treated wastewater from Joint Base Cape Cod (JBCC, formerly called Otis Air Base, Otis Air National Guard Base and Massachusetts Military Reserve) in Cape Cod, Massachusetts was disposed on the surface of sand beds at the southern border of the military base (Figure 1). Such treatment, called infiltration-percolation, was used to dispose of the treated sewage onto 12 acres of sand beds from 1936 to 1995 (LeBlanc, 1984). With this type of treatment, the wastewater swiftly infiltrates through the beds and moves deeper into the subsurface. Because of the shallow depth of the water table and the geology of the region of Cape Cod, the treated wastewater entered the groundwater system and created a plume of contaminants in the unconfined aquifer just south of the sand beds. The resulting plume was about 30 meters thick, 1.2 kilometers wide and almost 8 kilometers long some 20 years after disposal of the treated sewage on the sand beds ceased (Barbaro et al., 2013).

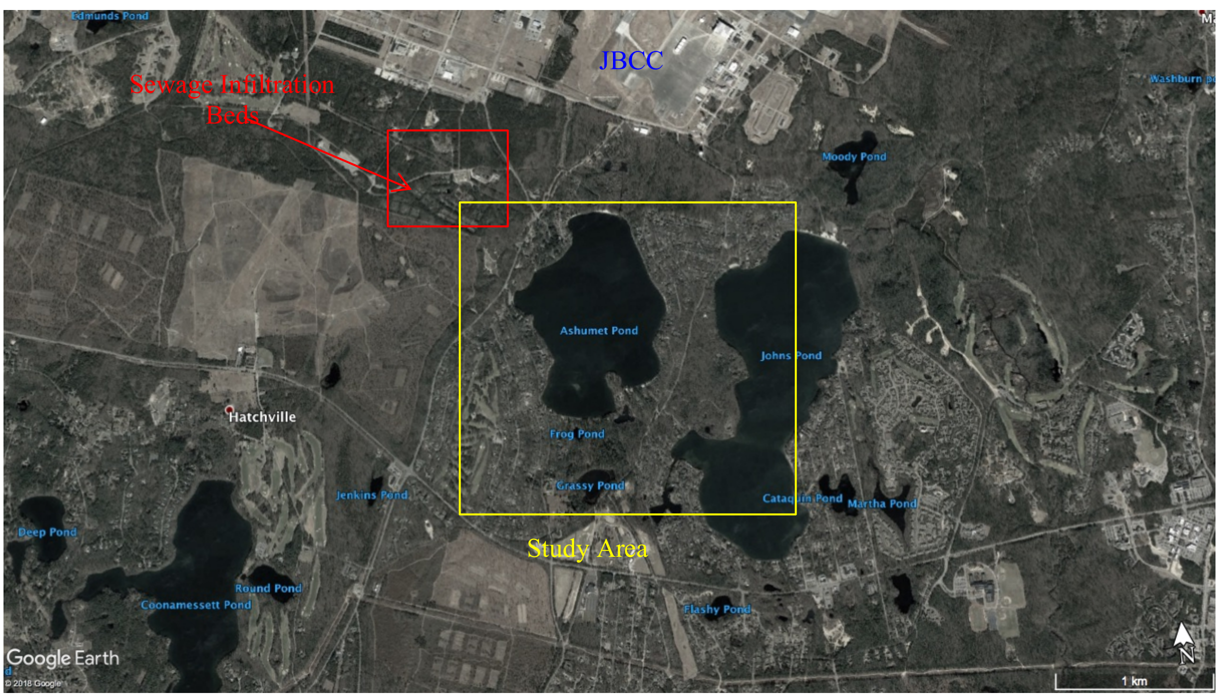

Figure 1. Area showing location of Ashumet Pond, Johns Pond and JBCC to the North. Location of the old infiltration beds is shown in the red box. Study area is shown in the yellow box. Image taken from GoogleEarthPro.

The contaminant plume contains an assortment of compounds typical of treated sewage from that time, including boron, chloride, nonbiodegradable detergents such as alkyl benzene sulfonate, and small quantities of trace metals and dissolved organic compounds (LeBlanc, 1984). The plume of the sewage also contains various nitrogen species, e.g., nitrate and ammonium, which have been the subject of many recent studies. These constituents are of concern because these they can react biologically in the environment, acting as nutrients for bacteria and algae (Shanahan, 1996). If these nutrients discharge into ponds or lakes in high enough concentrations, they can cause eutrophication of the surface waters. Eutrophication, defined as an excess of nutrients in a body of water, leads to an overgrowth of algae and plant life. This excess growth rapidly depletes the aquatic system of oxygen and can lead to the death of aquatic animals and release of harmful toxins (US Department of Commerce, 2004).

The two forms of nitrogen of interest in this paper are ammonium and nitrate. Both of these are common constituents of sewage from human waste and are present in the JBCC sewage plume (Barbaro et al., 2013). When these compounds infiltrate the subsurface, they commonly react biologically. There are two dominate reactions that occur in this situation: nitrification and denitrification. Both of these are bacterially mediated, meaning that the rate of the reactions is dependent on the biological composition of the subsurface. Nitrification is the oxidation of ammonium to nitrate, and the reaction is shown below as:

$$\mathrm{NH_4^+ + O_2 \rightarrow NO_3^- + H_2O + 2H^+}$$

The rate of reaction is dependent on the microorganisms present, and factors including pH, temperature, and the initial concentrations (Izbicki, 2014). Because oxygen is a reactant in this equation, the presence of large amounts of ammonium tends to deplete oxygen and create an anoxic to suboxic environment. Denitrification, described by the following reaction, is the process of reducing nitrate to nitrogen gas.

$$4NO_3^- + 5C + 2H_2O \rightarrow 2N_2 + 4HCO_3^- + CO_2$$

The presence of oxygen is the primary limiting factor for denitrification, and the microorganisms that mediate this process are pervasive (Izbicki, 2014).

South of the infiltration beds used for wastewater disposal are two ponds, Ashumet Pond and Johns Pond. Ashument Pond is located directly northeast of Johns Pond and is a 0.8 km^2 area pond with an average depth of 7 m. Johns Pond is slightly larger at 0.98 km^2 in area and also has an average depth of 7 m. These two bodies of water offer a multitude of recreational opportunities for the nearby community including: camping, kayaking, swimming, and most importantly fishing. Both ponds are annually or biannually stocked with rainbow and brook trout and also offer excellent bass fishing (Massachusetts DFW, 2007). However, the flow of contaminants from JBCC into the ponds has become a concern. The introduction of high levels of nutrients into the ponds could cause eutrophication and adversely affect the usability and environmental health of the ponds. Recent studies have shown that a plume of nutrients, which includes ammonium and nitrate, exists in the area between the infiltration beds and the northwest shoreline of nearby Ashumet Pond (McCobb et al., 1999). These effects have already been evident in Ashumet Pond since the 1970s in the form of fish kills and algae blooms (K-V Associates, 1991).

There is a possibility that the JBCC plume could flow from the infiltration beds and reach Johns Pond. The study area, represented by the yellow box in Figure 1, covers an area from the edge of the infiltration beds to the western shoreline of Johns Pond. The overall goal of this thesis is to provide a qualitative estimate of the time frame that the nitrate and ammonium from the JBCC sewage plume would take to infiltrate Johns Pond.

GEOLOGIC SETTING

Glacial History

Most of the important geologic features in the study area were formed as a result of the Wisconsin Glacial Episode towards the end of the Pleistocene Epoch. The Wisconsin Glacial Episode was the most recent period of glaciation that occurred in North America, which reached a maximum extent about 25,000 years ago (Oldale, 1976). The Laurentide ice sheet was important in shaping the land surface of most of northern North America. It covered nearly all of present-day Canada, New England and the Great Lakes regions at its maximum. The maximum extent of ice in the Cape Cod region is preserved as the prominent moraine deposits that form Martha's Vineyard and Nantucket Island, approximately 15 miles south of Johns Pond. A period of glacial retreat that occurred from approximately 21,000 to 15,000 years ago, (Oldale and Barlow, 1986) exposed the current area of Cape Cod before becoming stagnant and forming the Buzzards Bay Moraine and Sandwich Moraine north of the study area. This history of deglaciation is reflected in the moraine systems seen in Figure 2 and described by Oldale and O'Hara (1984). The final period of glacial retreat then occurred, exposing most of the previously ice-covered land surface leading to relatively minor Holocene processes on the land surface within the region.

Geology

Glacial processes controlled the near-surface deposits in the area, which are most relevant to the hydrogeological setting. The shallow subsurface in the area around Ashumet and Johns Ponds consists of outwash deposited at or in front of the end moraines (Olcott, 1995). More specifically, the upper 60 meters below the surface is composed of two deltaic glaciolacustrine units (Masterson, 1997). The uppermost unit is composed of unconsolidated, well-sorted coarse-grained sand and gravel, approximately 30 m thick. The second unit is composed of unconsolidated fine-grained sand and silt, and occurs approximately between 30 and 60 meters below the land surface (LeBlanc, 1984). These two units overlie an unsorted dense till deposit with lenses of sand, silt, clay, and scattered gravel, which is approximately 15 m thick. These deposits cap crystalline bedrock, which is approximately 75–90 meters below the land surface (Masterson, 1997).

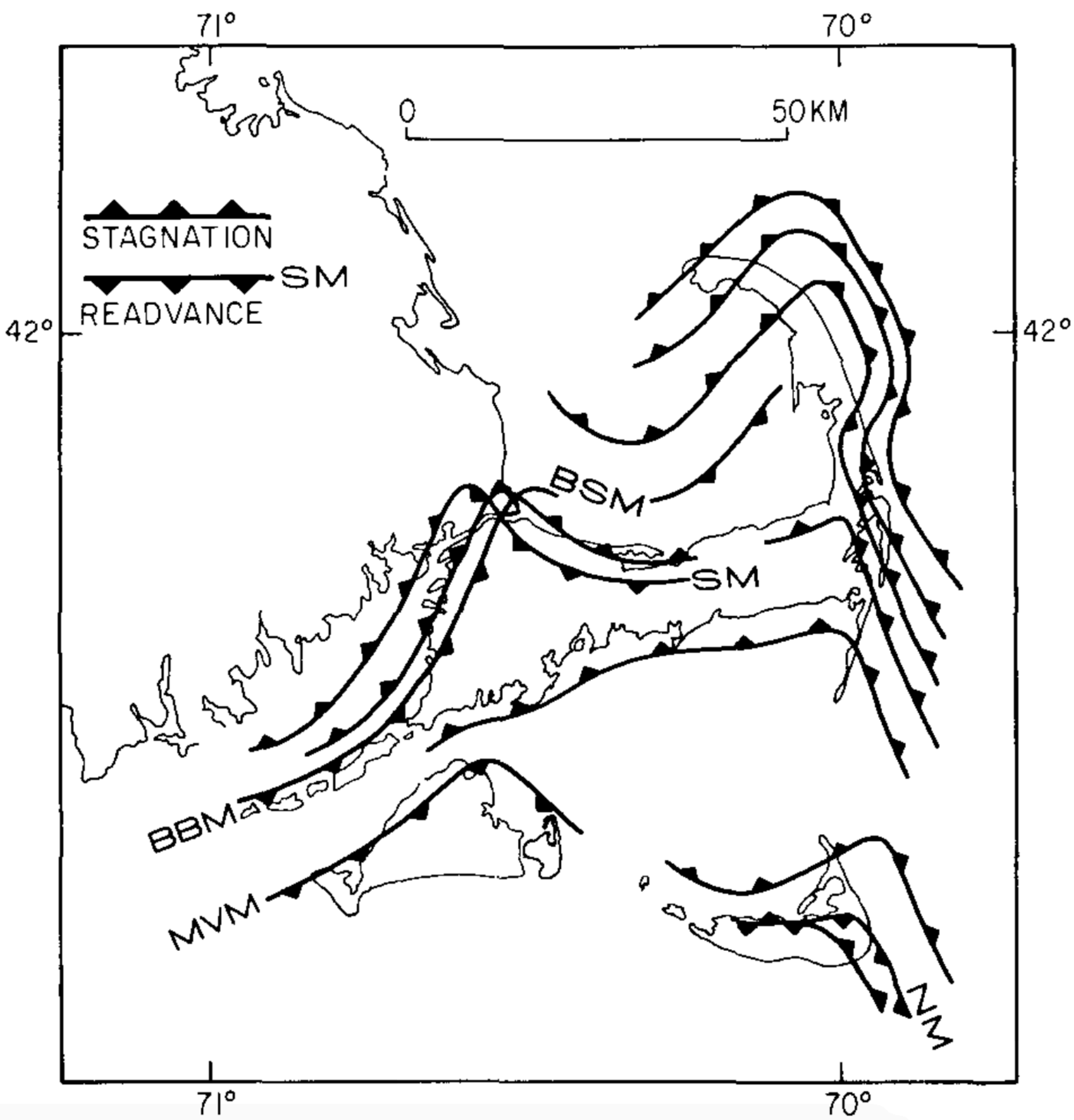

Figure 2. Moraine and ice front positions in the Cape Cod area at the end of the Pleistocene. BBM: Buzzards Bay Moraine, MVM: Martha's Vineyard Moraine. NM: Nantucket Moraine. SM: Sandwich Moraine. BSM: Billingsgate Shoal Moraine. Figure taken from Oldale and O'Hara (1984).

Hydrogeology

The coarse sand and gravel and the finer grained sediments act as an unconfined aquifer and provide the sole source of drinking water for the area (LeBlanc, 1984). This unconfined aquifer is known as the Cape Cod aquifer. The hydraulic conductivity differs significantly within the different units. The variability is mostly due to the difference in grain size of the different sediments. Beds composed of coarser grained material will allow groundwater to flow faster than finer-grained sediment. This means that the hydraulic conductivity of the sand and gravel is higher than the hydraulic conductive of both the finer sand and silt sediments and the dense till deposit. The hydraulic conductivity of the crystalline bedrock is orders-of-magnitude lower than either of the outwash deposits and it can be assumed that the upper surface of the bedrock is the bottom of the active groundwater flow regime (LeBlanc, 1984).

The Cape Cod aquifer has six distinct fresh ground water lenses. The area of Ashumet Pond and Johns Pond is located within the Sagamore lens, which is the largest lens, located in the western half of Cape Cod. The groundwater discharge from this lens is approximately 1 million cubic meters of fresh water daily and accounts for roughly 60 percent of the groundwater flow within Cape Cod (Walter et al., 2004).

Within the area of interest, the groundwater flows down gradient, in a direction perpendicular to the water table contours. Groundwater generally flows to the south but near Ashumet Pond and Johns Pond it has a local southwesterly flow direction. The elevation of the water table fluctuates 0–1 meters annually within this area (LeBlanc 1984). The groundwater system is almost entirely recharged by precipitation and the groundwater eventually discharges into streams, estuaries, wells and to Nantucket Sound and Vineyard Sound to the south of the study area. Ashumet Pond and Johns Pond are kettle ponds. Kettle ponds are formed from large ice blocks that are left behind from a retreating glacier (Oldale, 1976). There are no inflowing or outflowing streams in either of the ponds, and inflow is provided by groundwater, precipitation and surface runoff only. The two ponds are flow-through ponds, meaning that the groundwater flows into the ponds from up gradient flows and flows out of the pond downgradient. The pond outflow in the groundwater eventually is discharges into streams and wells down gradient of those ponds (Walter et al., 2004).

METHODS

Contaminant Flow Rate

The groundwater flow rate or linear groundwater velocity was estimated using Darcy's Law, Equation 1:

$$-v = \frac{K}{n}\frac{(dh)}{(dl)} \tag{1}$$

where v is the linear-groundwater velocity, K is the hydraulic conductivity, *(dh/dl)* is the hydraulic gradient, and n is the effective porosity. The hydraulic conductivity was estimated to range from 61 to 91 m/day and an effective porosity was estimated to be 0.2 to 0.4 for this aquifer (LeBlanc, 1984). The hydraulic gradient was calculated to be 0.00126 m_x/m_y and was found by using the change in water table elevation over the distance from Well A1 to A14 in Table 1.

The calculated value for hydraulic gradient and the estimated values for effective porosity and hydraulic conductivity gave a range of groundwater velocity values from 0.2 to 0.6 m/day. Because of the negative charge, the velocity of the nitrate in the plume was assumed to be the same as the groundwater velocity. Given the positive charge of the ammonium ion, one can expect that it will be sorbed, resulting in a velocity for ammonium v_a that is slower than the groundwater. The retardation factor (R_f) for ammonium or v/v_a describes how much slower ammonium travels relative to water. For this aquifer, R_f was 2.5. Thus, ammonium would move 2.5 times slower than that of nitrate because of sorption processes (Barbaro et al., 2013). This means that the ammonium plume is only moving at a rate of 0.08 to 0.2 m/day.

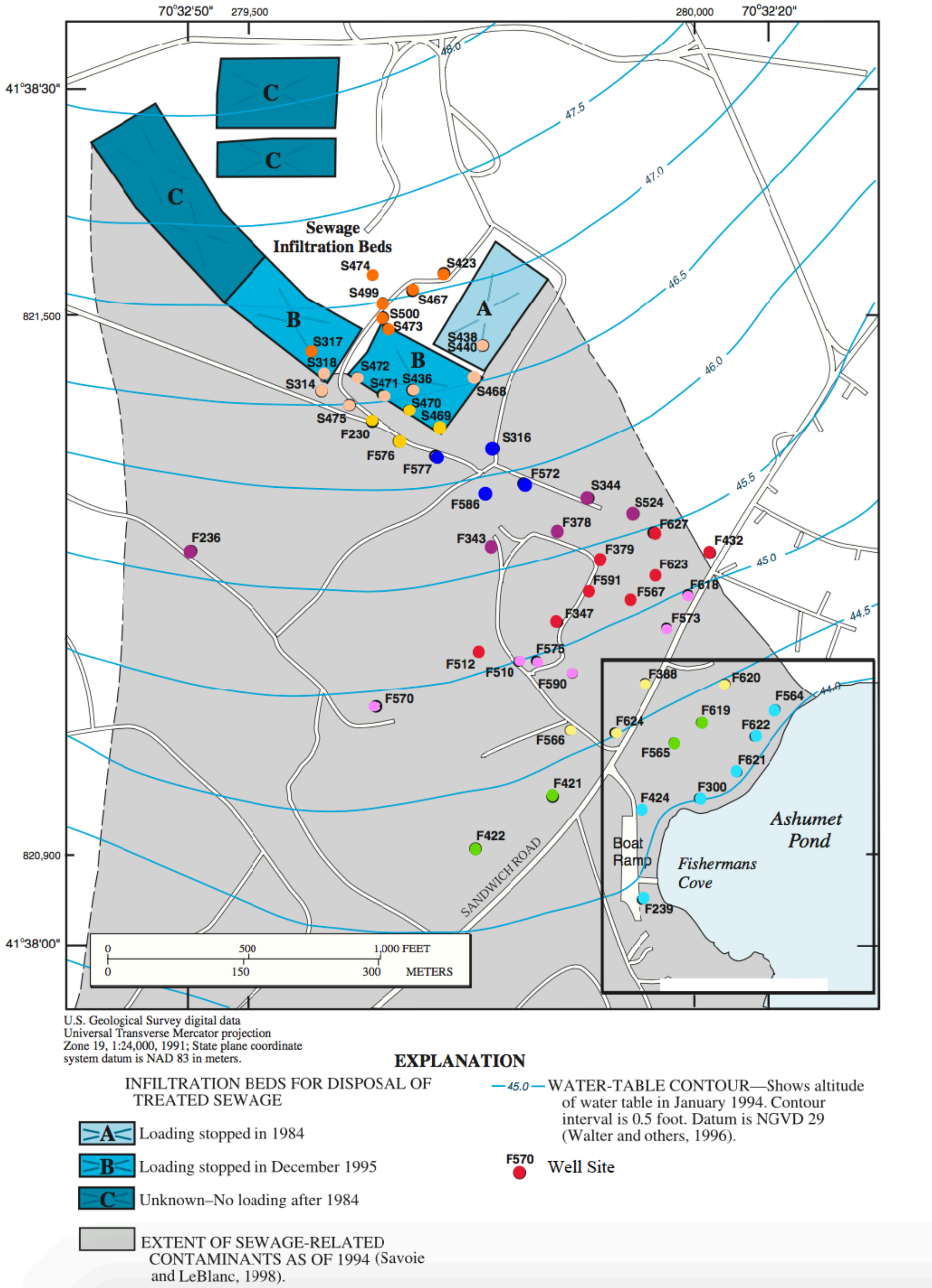

Figure 3. Map of well locations used for nitrogen concentrations. The colors represent the different sections. Orange: 1, Peach: 2, Gold: 3, Blue: 4, Purple: 5, Red: 6, Pink: 7, Yellow: 8, Green: 9, Light Blue: 10.
Adapted from McCobb & LeBlanc (1999).

Plume Mapping

McCobb et al., (1999) conducted a study of the plume extending from the northwest shoreline of Ashumet Pond to the infiltration beds. The data from their study, along with other USGS NWIS data, were used to create Figure 3. Most of the wells used were multilevel sampler wells. These wells are made of individual (usually around 15) plastic sample tubes connecting to screened ports that facilitating the vertical profiling of the aquifer across much of the aquifer (Miller and Smith, 2009). The maximum concentration of ammonium and nitrate measured at each well location was recorded along with the corresponding elevation of the screened port from which those concentrations were collected. Sampling and analytical methods and the well construction method can be found elsewhere (McCobb et al., 1999; LeBlanc, 1984).

The area shown in Figure 3 was then divided into 10 Sections, seen in Figure 4. The section boundaries were determined by distance from Ashumet Pond, and each section includes a slice of the plume immediately up gradient of Ashumet Pond. The maximum concentrations of NH_4 and NO_3 from each port of all wells within a section were averaged. The corresponding elevations were also averaged. This was done to provide a simpler way to analyze the distribution of key nitrogen compounds within the plume, as well as to better analyze the future impact on Johns Pond.

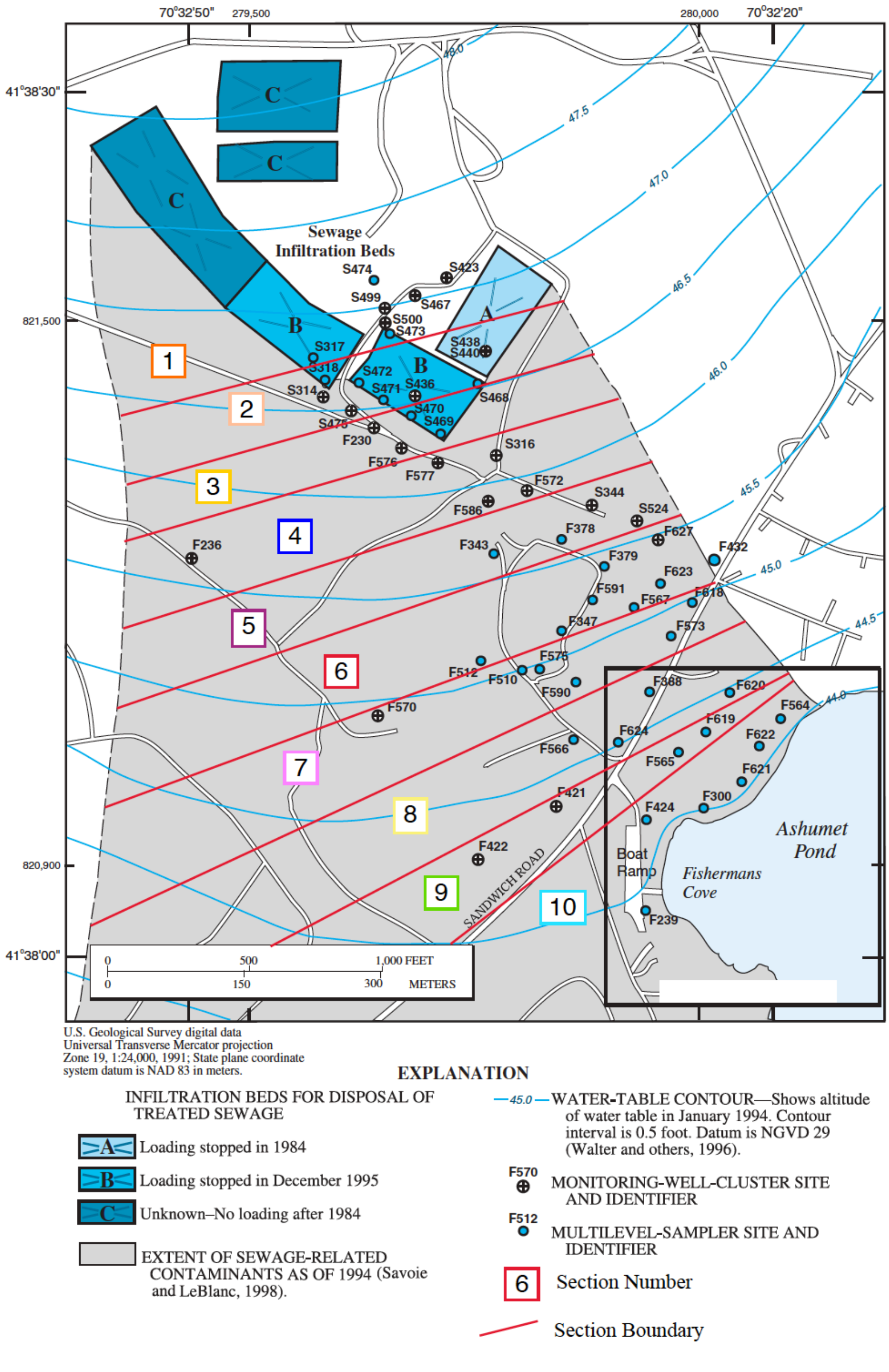

Figure 4. Map showing location of each Section. Adapted from McCobb and LeBlanc (1999)

Arrival Time Estimation

The time it would theoretically take for nitrate and ammonium to reach Johns Pond was calculated by using Equation 2:

$$t_i = d_A(1/v_i) + R_t + d_J(1/v_i) \quad (2)$$

where t_i is the time it takes for a contaminant particle, *i,* to reach Johns Pond, d_A is the distance between Ashumet Pond and the current location of a contaminant particle, R_t is the retention time of water in Ashumet Pond, d_J is the distance from Ashumet Pond and Johns Pond, and v_i is the flow rate of *i* in the groundwater. In this equation, the effects of recharge are ignored and it is assumed that a particle of contaminant *i* that enters into Ashumet Pond will flow outwards toward Johns Pond. The assumption of nonreactive particle transport is also made. This was done to simplify the scenario and to fit the scope of this thesis. Although this simplification may create an error in the calculated values, it provides a worst-case scenario for the timing of inflow of nitrate and ammonium into Johns Pond. R_t was assumed to be 1.89 years (K-V Associates, 1991). d_J was estimated to be 450 m using Google Earth. d_A varies from 0 m to 600 m depending the section, based on Figure 4, where the particle is located.

RESULTS

Cross Section

Figure 5 is a hydrologic cross section across the study area showing the land-surface and water-table elevation at 15 active USGS wells. The surface locations of Ashumet Pond and Johns Ponds are labeled on the cross section. Table 1 shows the data used to create Figure 5. These data were taken from the USGS website using the National Water Information System mapper tool.

Figure 6 is a map view of the cross section location and shows the location of each of the active wells in the study area and the cross section line though the wells used to create Figure 5.

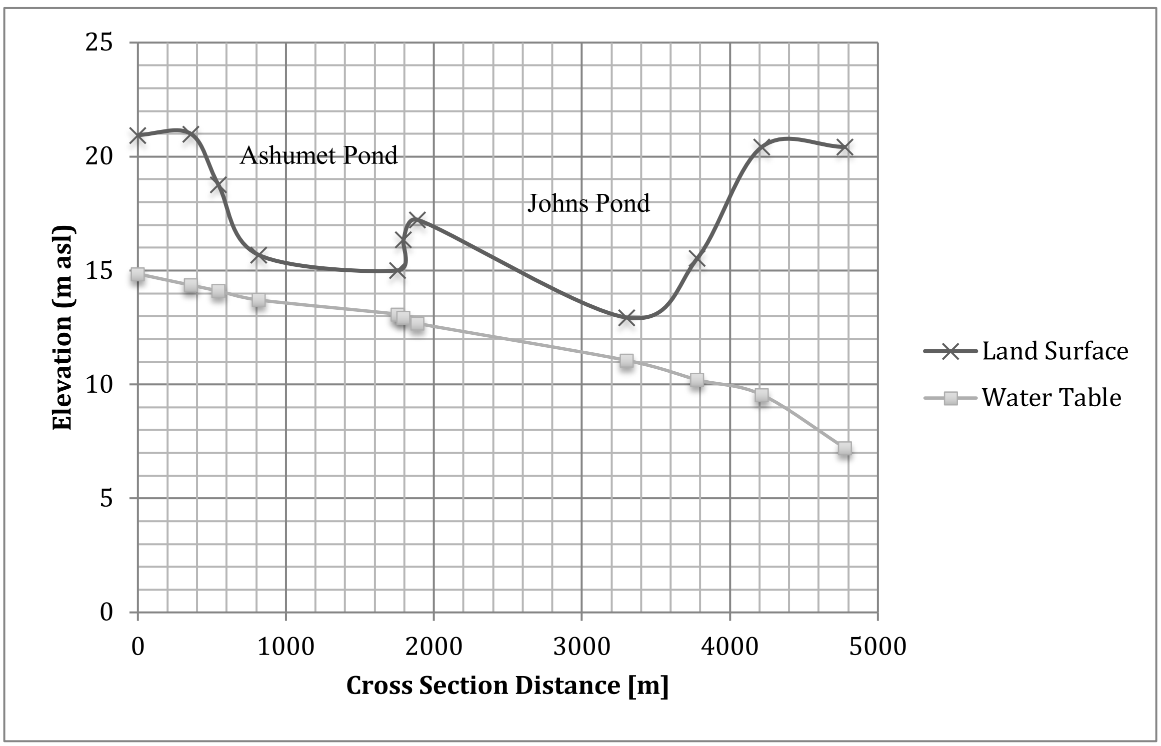

Figure 5. Hydrologic Cross Section through Ashumet Pond and Johns Pond.
Squares and X's represent the well locations

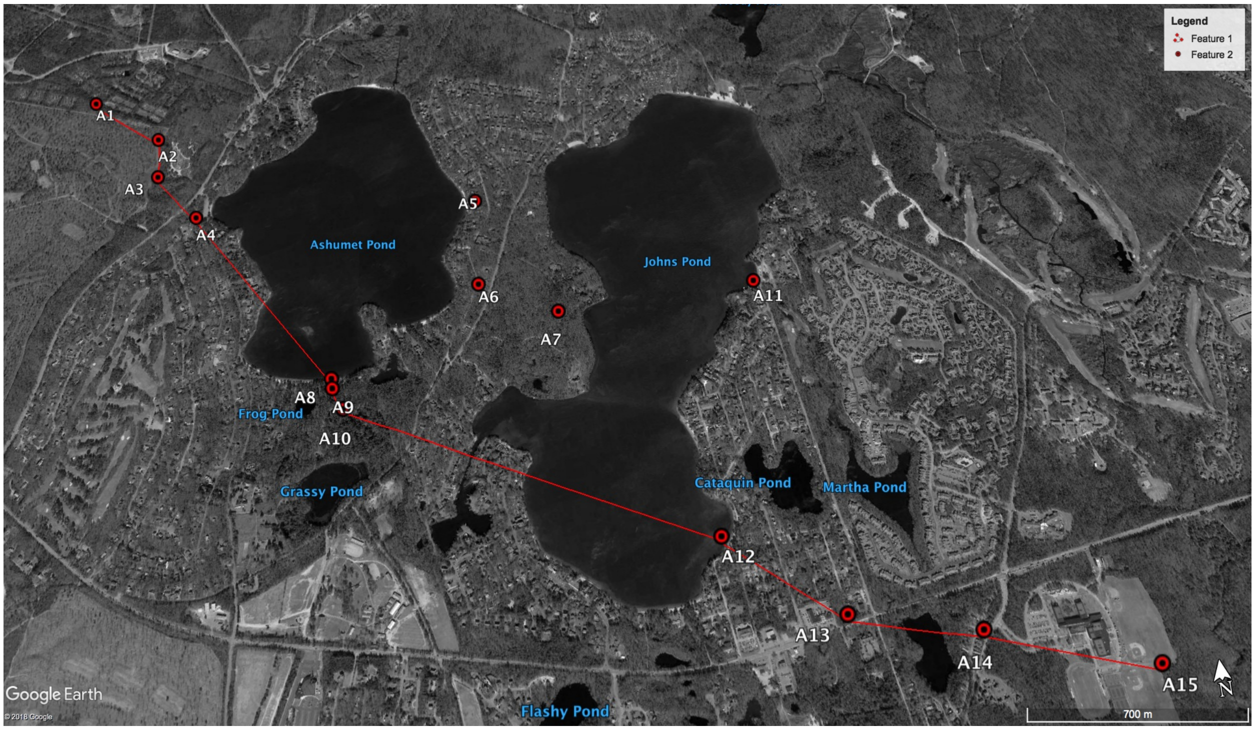

Figure 6. Map view of Study Area showing the active USGS wells and the cross section location of Figure 5. Image taken and adapted from GoogleEarthPro.

Table 1. Data used to construct Figure 4. * Dates means that the data were averaged from those dates.

Well	USGS Well Site	Date of Data Collection [month/yr]	X-sec Distance [m]	Well Elevation [m asl]	Water Table Height [m asl]
A1	413821070324504	06/16, 06/17*	0	20.94	14.85
A2	413814070323502	06/16, 06/17*	356	21.00	14.36
A3	413808070323501	06/16, 06/17*	542	18.78	14.11
A4	413801070322703	07/14, 07/17*	814	15.69	13.71
A8	413735070320731	06/17	1755	15.01	13.08
A9	413734070320616	06/17	1795	16.35	12.93
A10	413732070320503	06/17	1891	17.22	12.68
A12	413709070311202	06/17, 07/17*	3359	12.94	11.06
A13	413659070305604	06/17, 07/17*	3836	15.54	10.20
A14	413655070303801	06/17, 07/17*	4271	20.42	9.55
A15	413649070301401	06/17, 07/17*	4832	20.42	7.22

Contaminant Concentrations

A list of the greatest concentrations of nitrate and ammonium and the corresponding screen elevation associated with that concentration for each well were compiled into Table 2. The month and year of when the data were collected is also listed. The data were taken from USGS well site data using the National Water Information System mapper tool and from McCobb et al., (1999). Each data set was then sorted into a corresponding section, based on distance to nearby Ashumet Pond (Figure 5). Due to the large number of data points only the greatest measured concentration and the elevation at which it was measured were recorded for each well site.

Table 2. Highest measured NH_4 and NO_3 concentration and the corresponding elevation of each well.

			Ammonium		Nitrate	
Section	Well	Collection Date	Elevation (m asl)	Concentration (mg/L)	Elevation (m asl)	Concentration (mg/L)
1	S 317	06/1999	7.32	0.25	13.37	2.87
1	S 473	06/1999	6.25	1.64	13.67	3.75
1	S 474	06/1999	-0.55	0.10	9.92	2.72
1	S 423	07/1999	-2.50	0.03	8.31	3.05
1	S 467	07/1999	7.35	0.07	13.62	4.60
1	S 499	07/1999	6.42	1.23	-2.50	0.35
1	S 500	07/1999	6.27	1.50	7.35	0.04
2	S 318	06/1999	3.69	0.25	6.42	0.07
2	S 468	06/1999	9.82	0.13	6.27	0.06
2	S 471	06/1999	9.85	0.18	13.22	6.18
2	S 472	06/1999	-14.01	0.15	14.13	7.27
2	S 314	07/1999	8.47	0.11	14.11	2.84
2	S 436	07/1999	1.19	2.34	2.90	1.98
2	S 438	07/1999	13.11	0.08	-1.95	1.00
2	S 440	07/1999	0.84	0.04	14.02	2.15
3	S 469	07/1999	1.87	2.12	13.11	7.45
3	S 470	06/1999	-0.55	1.26	0.84	0.59
3	F 230	07/1999	-0.21	0.06	13.18	5.76
3	F 576	06/1999	-0.65	0.54	14.09	5.24

Table 2 continued						
			Ammonium		Nitrate	
Section	Well	Collection Date	Elevation (m asl)	Concentration (mg/L)	Elevation (m asl)	Concentration (mg/L)
4	F 572	05/1999	7.97	0.16	13.01	2.30
4	F 577	06/1999	4.40	0.17	13.54	5.37
4	F 586	07/1999	3.85	0.63	-1.17	1.35
4	S 316	05/1999	-11.47	0.15	12.85	3.41
5	F 343	05/1999	1.09	1.53	13.81	1.79
5	F 378	04/1999	8.38	0.15	8.40	3.01
5	F 236	05/1999	-1.95	0.10	10.82	4.15
5	S 344	05/1999	-9.09	0.23	0.98	3.10
5	S 524	05/1999	2.44	0.37	1.96	7.95
6	F 347	06/1999	-0.02	0.68	12.91	0.62
6	F 379	04/1999	-20.22	1.42	8.03	3.40
6	F 432	05/1999	-17.85	0.11	-20.22	2.22
6	F 512	06/1999	-5.14	0.48	10.45	3.90
6	F 567	05/1999	-17.63	2.41	10.64	3.82
6	F 591	05/1999	-11.83	0.22	-8.17	1.28
6	F 623	07/1999	1.44	1.30	1.22	0.72
6	F 627	05/1999	-4.27	0.22	-8.53	0.66
7	F 510	06/1999	10.45	0.14	-2.68	2.54
7	F 573	05/1999	-19.70	3.03	10.08	2.46
7	F 575	06/1999	-6.67	0.23	5.09	1.67
7	F 590	04/1999	10.08	2.46	-14.91	2.65
7	F 618	05/1999	-12.51	0.24	12.61	5.80
7	F 570	07/1999	-4.13	0.56	8.69	7.74
8	F 388	05/1999	-19.80	2.71	10.52	3.28
8	F 566	06/1999	-3.96	1.00	1.57	0.76
8	F 620	07/1999	-19.57	4.05	10.14	1.61
8	F 624	07/1999	-0.22	0.90	8.08	0.26
9	F 565	05/1999	-15.68	1.40	2.83	17.54
9	F 619	07/1999	-17.22	3.37	6.57	8.84
9	F 421	05/1999	8.08	0.04	-20.56	2.64
9	F 422	05/1999	-9.45	0.41	-19.66	2.46
10	F 300	05/1999	-5.15	2.26	-17.13	2.16
10	F 424	06/1999	-19.52	1.66	5.60	7.48
10	F 564	05/1999	-11.70	1.77	-11.70	3.03
10	F 621	07/1999	3.07	3.46	-19.49	2.84
10	F 622	07/1999	-19.96	4.69	-19.96	1.86
10	F 239	06/1999	-17.87	1.75	1.91	7.08

The average maximum concentrations and the corresponding elevations for each of the 10 sections were determined (Table 3). These data are also represented graphically in Figure 7 and Figure 8, to provide a rough visualization of the plume. Figure 7 shows the average maximum concentration of ammonium and nitrate as a function of location. Figure 8 shows the average depth of maximum contaminant concentration versus the section where the well was located.

Table 3. Average highest concentration and corresponding average elevation of each section.

		Ammonium		**Nitrate**	
Section	Number of wells in section	Average Concentration (mg/L)	Average Elevation (m asl)	Average Concentration (mg/L)	Average Elevation (m asl)
1	7	0.689	4.36	1.309	7.02
2	8	0.410	4.12	4.301	12.09
3	4	0.995	0.12	3.925	10.81
4	4	0.278	1.19	2.980	9.76
5	5	0.476	0.17	1.888	4.33
6	8	0.855	-9.44	2.591	-0.39
7	6	1.110	-3.75	3.695	7.54
8	4	2.165	-10.89	3.540	-3.30
9	4	1.305	-8.57	5.725	-7.33
10	6	2.598	-11.86	5.188	-6.18

Travel Time

Table 4 shows the calculated theoretical travel time for ammonium and nitrate in each section. The estimated distance to Ashumet Pond is also presented there, along with the number of wells located in each section. The maximum and minimum time, in years, was due to uncertainty of the estimate of porosity that yielded different estimates of travel velocity when calculated from Equation 1. This then gives a range of time for the arrival of nitrate or ammonium to Johns Pond. The theoretical travel route of nitrate and ammonium was assumed to roughly follow the cross section line in Figure 4.

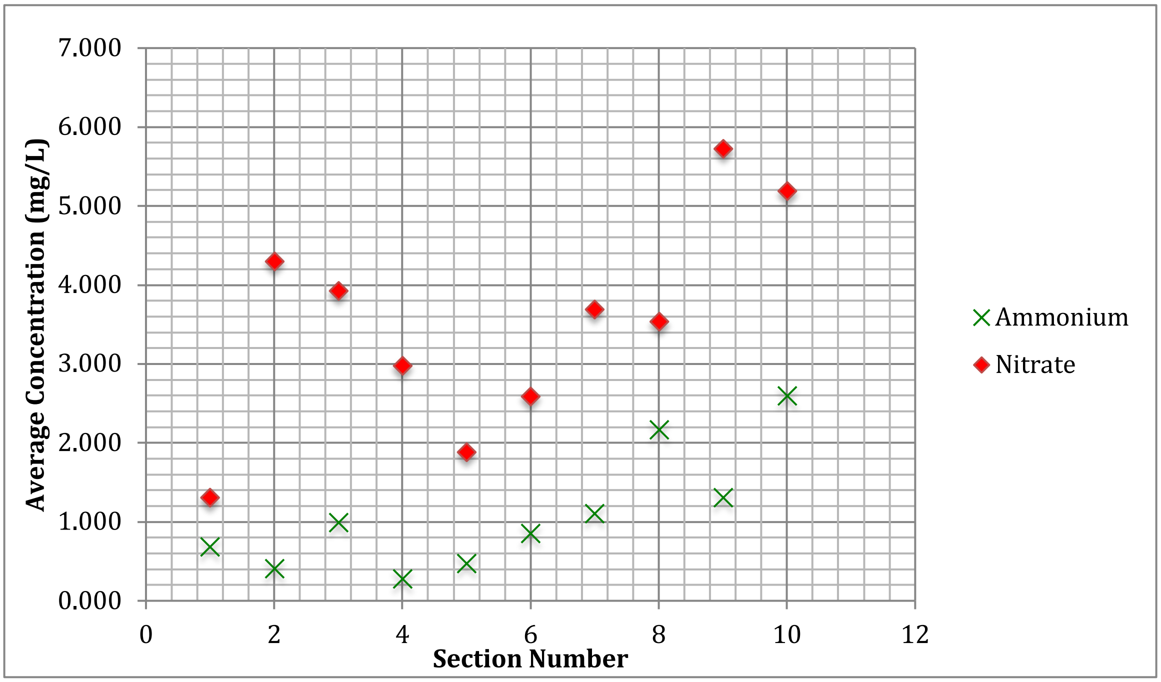

Figure 7. Graph of average highest concentration for each section.

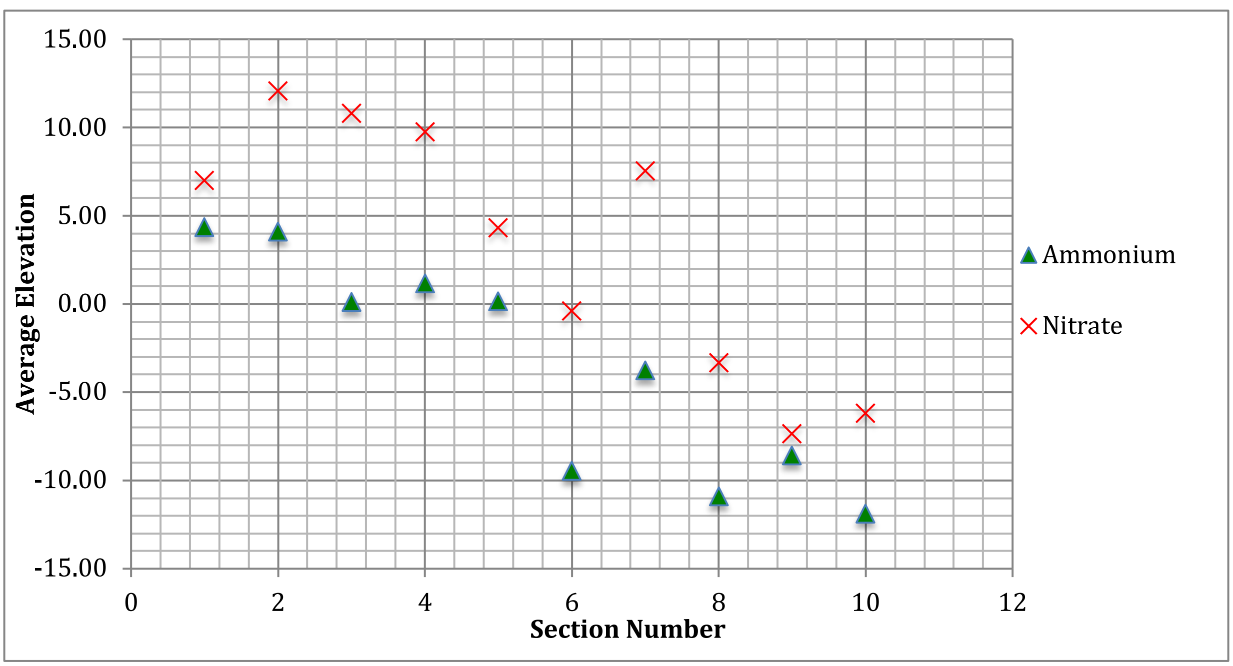

Figure 8. Graph of average elevation of highest measured concentration for each section.

Table 4. Time, in years, for a contaminant particle in a section to reach Johns Pond

	Nitrate		Ammonium	
Section	Max Time (yr)	Min Time (yr)	Max Time (yr)	Min Time (yr)
1	16.27	6.68	37.85	14.39
2	15.29	6.36	35.38	13.54
3	14.38	6.05	33.12	12.75
4	13.48	5.75	30.86	11.96
5	12.57	5.45	28.60	11.18
6	11.67	5.15	26.34	10.39
7	10.77	4.85	24.08	9.60
8	9.86	4.55	21.82	8.82
9	8.96	4.25	19.56	8.03
10	8.05	3.94	17.30	7.25

DISCUSSION

Assumptions and Generalizations

The sewage plume at Cape Cod is an enormous and problematic plume. Thus the difficulty of estimating the time it takes for two of the compounds to travel a certain distance is rather complex. In order to simplify the problem to something that is within the scope and capabilities of this thesis, assumptions and generalizations were made.

The well data used were assumed to represent a snapshot in time of the plume. In reality, it is practically unachievable to test all the wells at the same moment in time. However, this was best accounted for by selecting data all within a four month period of time in the year 1999.

A major simplification was that non-reactive transport of nitrate and ammonium occurred. Processes such as nitrification and denitrification can decrease the amount of nitrogen in the groundwater (Miller and Smith, 2009). Some studies suggest, however, that the effect of these processes on the mass of nitrate is insignificant (Barbaro et al., 2013). However, the loss of ammonium could be significant. It has been estimated that about 3% of the mass of ammonium in the Cape Cod plume could be lost to microbial processes annually, and the effects of such losses were not accounted for (Barbaro et al., 2013).

Another assumption made was that only flux of water in and out of Ashumet Pond is from groundwater flow, and the effect of evapotranspiration and recharge due to runoff and precipitation are ignored. This was done purely to simplify the problem, as incorporating and accounting for surface hydrologic data was beyond the scope of this thesis. By doing this, the retention time that was used to calculate the flow of nitrogen through Ashumet Pond has an error that was not accounted for. Because of the above assumptions, the calculated values should be taken as a qualitative assessment of the problem rather than a quantitative determination.

Sections 1–4

These sections are located the farthest north and represent the start of plume, with sections 1 and 2 directly over top the infiltration beds, and sections 3 and 4 extending approximately 300 m down gradient from the sewage beds. The elevation of the plume in these areas is closest to the surface, ranging from 0.1 to 4.4 meters asl for ammonium and 9.8 to 12.1 meters asl for nitrate. Because the area represented by these sections is mostly directly below the sewage infiltration sand beds, the highest average concentrations should be closest to the surface here, especially because ammonium can be sorbed. The sewage would percolate through the beds before infiltrating to the water table and entering the groundwater flow regime. This would mean that the plume would have less opportunity to diffuse vertically before being transported horizontally down gradient. The average maximum concentrations of ammonium in these sections ranged from 0.28 to 1.0 mg/L with the highest concentration found in section 3 and lowest in section 4. The average maximum nitrate concentrations had a higher variance than ammonium of 1.3 to 4.3 mg/L. The locations of these highest average values were found in section 1 and 2 respectively.

The calculated times for the nitrate in these sections to reach Johns Pond ranged from about six to 16 years. Because this part of the plume is the farthest away from Ashumet Pond, this roughly represents the maximum time it would take for the nitrogen analyzed in this thesis to reach Johns Pond. Because the maximum travel time is only slightly above 16 years, all of the nitrate should have reached Johns Pond because the concentration data were obtained in the summer months of 1999. The calculated times for an ammonium particle to reach Johns Pond for these sections ranged from 12 to 38 years. This means that it is possible for all the ammonium to have discharged into Johns Pond, but is most likely some of it would still be travelling.

Sections 5–7

These sections represent the middle portion of the study area and are located in the region between 150 and 300 meters up gradient from Ashumet Pond, represent by the purple, red and pink colored well locations on Figure 3. The elevation of the ammonium and nitrate plumes is lower than in the region just northwest represented by my Sections 1–4. This is represented by the depth of the average maximum concentrations ranging from 0.17 to -9.4 m asl for ammonium and 7.5 to -0.39 m asl for nitrate. This vertical dip is possibly caused by the diffusion of the plume and from recharge from the surface.

The concentrations of nitrogen in these sections are similar to those found in Sections 1 through 4. The average maximum concentration of ammonium ranged from 0.47 to 1.1 mg/L at Section 5 and Section 7 respectively. The average maximum nitrate concentration ranged from 1.9 to 3.7 mg/L also at Sections 5 and 7 respectively.

The calculated time for the nitrate in these sections to reach Johns Pond ranged from 5 to 13 years. The same conclusion is made as the previously discussed sections, that all of the nitrate should have reached Johns Pond sometime between the years 2004 and 2012. The time for ammonium in these sections to reach Johns Pond was calculated to be between 9 and 29 years. This means that it the ammonium from the middle portion of the plume is likely either already being seen or will be within the next decade.

Sections 8–10

These three sections represent the southern portion of the plume within the study area in the region from the northwestern shoreline of Ashumet Pond to approximately 150 meters up gradient. The wells that represent these sections are the yellow, green and light blue colored well sites on Figure 3. The elevations of the nitrogen plume in this region are the lowest within the study area. For ammonium, the elevation of average maximum concentration ranged from -8.5 to -11.9 meters asl. The nitrate plume elevation coinciding with average maximum concentration ranged from -3.3 to -7.3 meters asl. As with Sections 5 through 7, this probably results from diffusion and recharge from the surface, which promoted the oxidation of ammonium to nitrate. The effect of Ashumet Pond acting as a flow-through pond is not seen in these data. The groundwater should flow vertically upward into Ashumet Pond; however, no observation of upward flow is mostly likely a result of looking at maximum concentrations for each well only and not all of the available data. In addition, discharge to the pond will occur close to the shoreline, which is not well instrumented.

The average maximum concentration of ammonium in this region ranged from 1.3 to 2.6 mg/L, and the average maximum concentration of nitrate ranged from 3.5 to 5.7 mg/L. These are the highest measured values of both nitrate and ammonium in the groundwater within the study area.

The calculated travel time to Johns Pond from this region varied from 4 to 10 years, and 7 to 22 years for nitrate and ammonium respectively. The same conclusion that nitrate has already reached Johns Pond is made. The ammonium from this region has likely already reached Johns Pond or will do so within the next few years.

Nitrogen Plume Geometry

A review of the 10 sections suggests that the concentration of nitrate and ammonium are mostly independent of horizontal distance. This can be explained by the variability in the flux of sewage from the infiltration beds, which would depend mostly upon the rate and type of sewage being deposited onto the infiltration beds and the quantity of precipitation and runoff that recharge the sand beds. For example, during WWII, the facility supported large numbers of troops, which would increase the flux of sewage onto the infiltration beds. In later years, the number of personnel on the base was much smaller. This factor created a highly variable distribution of contaminants within the plume.

However, there is a clear dependence of depth on the concentration and location of nitrogen. The maximum concentrations of ammonium are mostly found at lower elevations than nitrate, meaning that the nitrate appears to sit on top of ammonium plume. This is most likely a result of bacterially mediated oxidation of ammonium. The center of the ammonium plume is located in a low-oxygen environment, and as the elevation increases, oxygen becomes more accessible. This allows for nitrification to occur, and ammonium is oxidized to nitrate. This pattern of occurrence of nitrate in relation to the bulk of the anoxic plume containing ammonium has been seen previously in the Cape Cod region (Lee and Bennett, 1998).

CONCLUSIONS

It was found that it would take a maximum of 17 years for the nitrate currently present northwest of Ashumet Pond to reach Johns Pond, and it would take the end of the ammonium plume a maximum of approximately 38 years to reach Johns Pond from the time the data were collected in 1999. This means that the nitrate should have reached Johns Pond by 2016, and the ammonium by 2037. My study then suggests that the effects of an increase in nitrogen levels in the Johns Pond ecosystem should have already been evident, but evidence for this is lacking. This concern already exists in the community (Massachusetts DFW, 2007), as the sewage plume could adversely affect the environment, health and safety of Johns Pond and the local area for decades to come.

The USGS used the sewage plume at JBCC primarily as an opportunity to study contaminant transport processes in a simple setting at a site with easy access and the ability to drill many holes. Although the site is evidently contaminated, the levels of contamination are relatively low. For example, only a few samples exceeded the regulatory MCL for nitrate (10 mg/L). Thus, while the problem is serious, dilution and other processes have meant that the plume's impact on the ponds is quite modest.

RECOMMENDATIONS FOR FUTURE WORK

Possible research that would extend this study would be to create a more quantitative model of the hydrology of Ashumet Pond and the flow towards Johns Pond. Such a study would involve adding active monitoring well sites to the area between the ponds, in Johns Pond and southeast of Johns Pond. Addition of new wells would allow for updated data and monitoring capabilities to better predict the impact of the sewage plume on the ecosystem and local community. Another beneficial undertaking would be to monitor the nutrient levels in Ashumet Pond and Johns Pond.

A second useful extension of the study would involve an investigation of the transport phosphorous of compounds in the groundwater. In most settings phosphorous is strongly sorbed to grains producing a significant retardation relative to the groundwater velocity. Also, in some lake settings, phosphorous turns out to be the most important nutrient species contributing to eutrophication.

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